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The effect of (strong) discrete absorption systems on the Lyman α forest flux power spectrum

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ABSTRACT

We demonstrate that the Lyman α forest flux power spectrum of 'randomized' quasi-stellar object (QSO) absorption spectra is comparable in shape and amplitude to the flux power spectrum of the original observed spectra. In the randomized spectra a random shift in wavelength has been added to the observed absorption lines as identified and fitted with VPFIT. At $0.03\ \mathrm{s\,km^{-1}} < k < 0.1\ \mathrm{s\,km^{-1}}$ the '3D' power spectrum of the randomized flux agrees with that of observed spectra within the errors. At larger scales it still approaches 50 per cent of that of the observed spectra. At smaller scales the flux power spectrum is dominated by metal lines. Lines of increasing column density contribute to the '3D' flux power spectrum at increasingly larger scales. Lines with $13 < \log(N_{\mathrm{H\,I}}/\mathrm{cm^{-2}}) < 15$ dominate at the peak of the '3D' power spectrum while strong absorbers with $\log(N_{\mathrm{H\,I}}/\mathrm{cm^{-2}}) > 15$ contribute at large scales, $k < 0.03\ \mathrm{s\ km^{-1}}$. We further show that a fraction of $\gtrsim$15 per cent of the mean flux decrement is contributed by strong absorbers at $z \gtrsim 2.1$. Analysis of the flux power spectrum which use numerical simulations with too few strong absorption systems calibrated with the observed mean flux may underestimate the inferred rms fluctuation amplitude and the slope of the initial dark matter power spectrum.

Key words: intergalactic medium – quasars: absorption lines – large-scale structure of Universe.

1 INTRODUCTION

In the mid-1990s a paradigm shift occurred in the interpretation of the Lyman α forest. Instead of being caused by small (kpc size) 'Lyman α clouds' it is now widely believed that most of the absorption arises from smooth fluctuations in the density of a photoionized warm intergalactic medium (see Rauch 1998; Weinberg et al. 1999, for reviews). Traditionally, absorption spectra had been decomposed into Voigt profiles which have then been identified with individual discrete absorption systems. The column density, Doppler parameter distribution and correlation function were determined for these absorbers (Rauch 1998). With the new paradigm the emphasis of the analysis has shifted to statistical measures more suitable for absorption arising from a continuous density field, most notably the flux decrement distribution and the flux power spectrum. Numerical simulations show that in this new paradigm only strong absorption systems [$\log(N_{\mathrm{H\,I}}/\mathrm{cm^{-2}}) \gtrsim 15$; somewhat dependent on redshift and assumed ultraviolet (UV) background] are discrete, in the sense that they are not broadened by the Hubble flow [see, however, the discussion in Schaye (2001) about the size of the absorbers]. For lower column density systems, Hubble flow broadening becomes increasingly important. While the clustering signal in the correlation function of discrete absorbers was very weak for all but the strongest absorption systems (Cristiani et al. 1995), the flux power spectrum indicated rms fluctuations of 10–30 per cent on scales of a few Mpc, decreasing as a power law towards larger scales. This was generally interpreted as a detection of the clustering of the matter distribution. Due to non-linear and saturation effects, the relation to the dark matter (DM) power spectrum is not straightforward even on large scales. Numerical simulations are therefore used to constrain amplitude and slope of the matter power spectrum. The constraints are broadly consistent with the so called concordance model of structure formation (Croft et al. 1999; McDonald et al. 2000; Croft et al. 2002; Kim et al. 2004, hereafter K04; Viel et al. 2004). Recently a combined analysis of Lyman α forest and *WMAP* data has been used to argue that a spectral index of the initial matter fluctuation spectrum < 1 and/or a running running spectral index is indicated by the data (Spergel et al. 2003; Verde et al. 2003). However, inferring the matter power spectrum from the flux power spectrum is a non-trivial matter (Zaldarriaga, Hui & Tegmark 2001; Gnedin & Hamilton 2002). In particular, Zaldarriaga, Scoccimarro & Hui (2003) and Seljak, McDonald & Makarov (2003) have argued that Croft et al. (2002) underestimated the error in the mean flux decrement and therefore underestimated the errors in the slope and amplitude of the matter power spectrum (K04). The reason why

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the clustering signal in the correlation function of weak absorption systems is apparently so much weaker than that in the flux power spectrum has not been investigated in detail. Press, Rybicki & Schneider (1993) have demonstrated that the rms fluctuation of the flux distribution on scales of 25 Å due to randomly distributed absorption lines is comparable to the observed fluctuations. Zuo & Bond (1994) have shown that the flux correlation function of low-resolution absorption spectra can be reproduced by a superposition of randomly distributed absorption lines. Viel et al. (2004) have studied the effect of a random distribution of lines on higher order flux statistics such as the flux bispectrum.

Here we have studied the flux power spectrum of a sample of eight randomized high-resolution absorption spectra taken with the Ultra-Violet Echelle Spectrograph (UVES) on the Very Large Telescope (VLT) for which a complete decomposition into Voigt profiles due to hydrogen and metal lines absorption lines had been performed previously (Kim, Cristiani & D'Dodorico 2001; Kim et al. 2002). In Section 2 we describe the data. Section 3 compares the flux power spectrum of randomized and observed spectra. Section 4 investigates the effect of strong absorption systems. In Section 5 we discuss consequences for the inferred DM power spectrum and in Section 6 we give our conclusions.

2 THE DATA

The sample consists of eight spectra taken with the VLT-UVES. The eight spectra were taken from the ESO archive. The median redshift of the absorbed regions in the sample is $\langle z \rangle = 2.43$. In Table 1 we list the Lyman α redshift range, wavelength range and signal-to-noise ratio (S/N) of the sample. The data reduction is described in Kim et al. (2001, 2002, 2004). Line lists for hydrogen and metal absorption have been compiled with the fitting routine VPFIT (Carswell et al.: http://www.ast.cam.ac.uk/rfc/vpfit.html). For each of the eight spectra we have produced randomized spectra where we have randomly shifted the hydrogen lines in wavelength. This procedure results in spectra with a column density distribution that is very similar to that of the observed spectra. Note, however, that there will be some incompleteness at the low column density end due to lines which have not been identified by the fitting procedure due to blending. We have also produced randomized spectra where we restricted the input list of hydrogen lines to certain column density ranges.

3 THE FLUX POWER SPECTRUM OF RANDOMIZED SPECTRA

3.1 Calculating the flux power spectrum

The observed intensity is related to the emitted intensity as $I_{\rm obs} = I_{\rm em}\, {\rm e}^{-\tau}$. The fluctuations in the observed intensity are thus a superposition of the fluctuations of the emitted intensity and those of the absorption optical depth. We use here continuum-fitted spectra and consider the quantity $F = I_{\rm obs}/I_{\rm em} = {\rm e}^{-\tau}$ ('F1' in the notation of Kim et al. 2004). Our procedure for calculating the flux power spectrum is described in detail in K04 and we give here just a short summary.

Table 1. QSO absorption spectra.

QSO	$z_{\rm Ly\alpha}$	$\lambda_{\rm Ly\alpha}$ (Å)	S/N
Q0055–269	2.93–3.61	4778–5603	30–75
Q0302–003	2.95–3.24	4807–5156	55–75
HE2347–4342	2.29–2.84	4002–4669	40–60
Q1101–264	1.65–2.11	3224–3780	30–70
HE1122–1648	1.88–2.37	3507–4098	35–65
HE1347–2457	2.05–2.57	3711–4352	50–70
HE2217–2818	1.88–2.38	3503–4107	35–60
J2233–606	1.74–2.22	3337–3912	30–50

The '3D' flux power spectrum is obtained via numerical differentiation of the 1D flux power spectrum,

$$P_{\rm F}^{\rm `3D'}(k) = -\frac{2\pi}{k}\frac{\rm d}{{\rm d}k}P_{\rm F}^{\rm 1D}(k). \qquad (1)$$

The dimensionless '3D' power spectrum is given by,

$$\Delta^2_{\rm F}(k) = \frac{1}{2\pi^2}k^3 P_F^{\rm `3D'}(k). \qquad (2)$$

Jackknife estimates are used to calculate the errors. In order to remind the reader that peculiar velocities and thermal broadening make the flux field anisotropic, and that equation (2) does not give the true 3D power spectrum, we denote it as the '3D' power spectrum as in K04.

3.2 Flux power spectra of observed and randomized absorption spectra

In Fig. 1(a) we compare the 1D flux power of the sample of observed spectra to that of a sample of randomized spectra. For each observed spectrum we have produced 150 randomized versions. The errors of the randomized spectra are those due to the randomization only and are thus small. At wavenumbers $0.03\ {\rm s\ km^{-1}} < k < 0.1\ {\rm s\ km^{-1}}$ the 1D flux power spectra are remarkably similar. This agrees well with the result by Croft et al. (1998), who found that at these scales the matter power spectrum inferred from mock spectra obtained from a CDM simulation and that inferred from spectra with a random superposition of lines are also very similar. At larger scales the flux power spectrum becomes close to constant as expected for a random distribution of discrete absorption features. This suggests that the shape of the absorption lines as identified by a Voigt profile fitting routine contributes to the flux power spectrum over a wide range of scales. The discrepancy at $k > 0.1\ {\rm s\ km^{-1}}$ is expected, as the flux power spectrum of the observed absorption spectra is dominated by metal lines at these small scales (K04) which are not included in the randomized spectra. The contribution of large-scale correlations in the density field is responsible for the difference at large scales, but astonishingly these appear to be a relatively small contribution to the overall flux power spectrum. To investigate this in more detail we plot the corresponding '3D' flux power spectra in Fig. 1(b). As suspected from inspection of Fig. 1(a) at the peak, the '3D' flux power spectra are identical to within the errors. At larger scales the variance of the randomized spectra still approaches 50 per cent of that of the observed spectra. This may explain why Cristiani et al. (1995) only found a very weak signal for strong absorption systems when they investigated the clustering of absorption lines. It may also explain why linear theory gives a bad approximation to the '3D' flux power spectrum, even at scales $k \sim 0.003$–$0.001\ {\rm s\ km^{-1}}$ (Croft et al. 2002) and why numerical simulations, which can properly simulate the spatial distribution of the absorbers, are essential for inferring the DM power spectrum on these scales. The rather large contribution of a random superposition of Voigt profiles at $k < 0.02\ {\rm s\ km^{-1}}$ is slightly at odds with the conclusion of Croft et al. (1998) that a random superposition of lines is consistent with no contribution at these scales. Note, however, that the error bars in Croft et al. were very large and that their study was at somewhat higher redshift. We

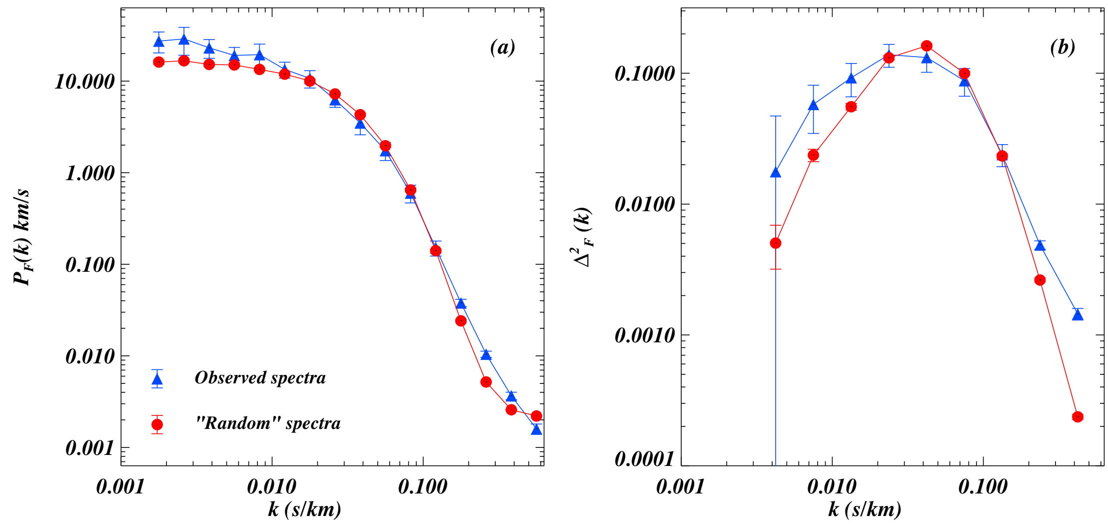

Figure 1. *Left:* the 1D flux power spectrum of a sample of observed and randomized spectra. *Right:* '3D' power spectrum.

therefore do not think that the Croft et al. results are necessarily in conflict with our results, which are based on observed spectra alone and addresses this question more directly.

4 THE EFFECT OF STRONG DISCRETE ABSORPTION LINES

4.1 Strong absorption lines and the flux power spectrum

In Fig. 2 we have split the '3D' flux power spectrum of the spectra into contributions from lines of different column density ranges. Lines of different column density ranges do not add exactly linearly, but the relative contributions should nevertheless become apparent in this way. In the left-hand panel we show the split for the observed spectra. The right-hand panel shows the same split for the randomized spectra where averaging over many random realizations of spectra with exactly the same column density distribution reduces the noise considerably. There is a clear trend with larger column density systems contributing at larger scales. The strongest contribution comes from absorption lines in the range $13.5 < \log(N_{\rm H\,I}/{\rm cm}^{-2}) < 14.5$. These are lines where the 'curve of growth' which describes the relation between equivalent width and column density of absorption lines changes from the linear to the flat regime due to saturation. Such a behaviour can be understood if the different column density ranges contribute with their total equivalent width (EW), $\mathcal{N}_{\rm lines} \times$ EW, to the '3D' power spectrum. The number of lines scales roughly as as $\mathcal{N}_{\rm lines} \propto N_{\rm H\,I}^{-0.5}$. The contribution to the total equivalent width has therefore a maximum for column densities at the transition of the curve of growth from linear to flat. Note that Press et al. (1993) had already demonstrated that the rms fluctuation of the flux can be explained with randomly distributed lines with a contribution $\propto EW^2$ to the 1D variance of the flux. Seljak (2000) has discussed the relative contribution of halo–halo correlation and the correlation of galaxies within DM haloes to the galaxy power spectrum which may to some extent be a related problem.

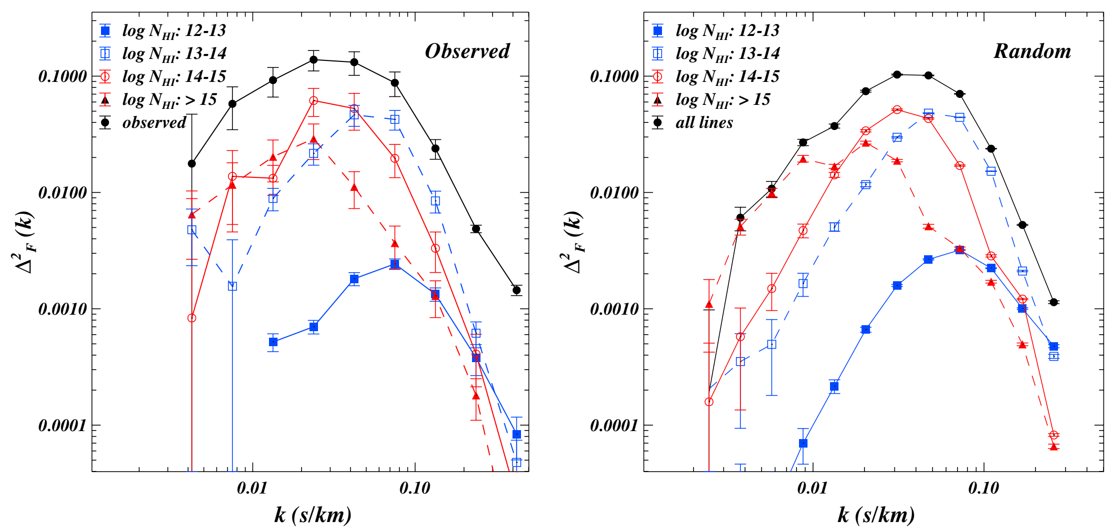

Figure 2. *Left:* contribution of different column density ranges to the '3D' flux power spectrum for the observed set of spectra. *Right:* contribution of different column density ranges to the '3D' flux power spectrum for the randomized set of spectra.

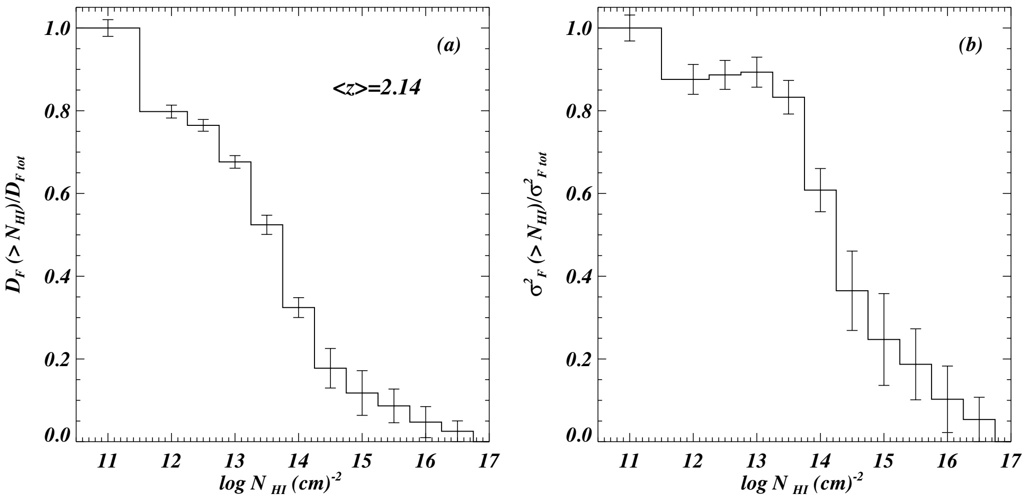

Figure 3. *Left:* cumulative distribution of the contribution of different column density ranges to the mean flux decrement of four observed spectra. *Right:* same for the rms amplitude of the flux.

4.2 Strong absorption lines and the mean flux decrement

By increasing size of the data sets, the mean flux decrement of absorption spectra has been determined reasonably well (Press et al. 1993; Rauch et al. 1997; Kim et al. 2002; Bernardi et al. 2003). It is nevertheless striking that the mean flux decrement varies considerably between different quasi-stellar objects (QSOs). The main reason for this is likely to be the large contribution of strong absorption systems. In Fig. 3(a) we have used the bottom four of the spectra listed in Table 1 to quantify the contribution of absorption lines in different column density ranges to the mean flux decrement by successively removing low column density lines. These four spectra were chosen because they are at similar redshifts and thus have comparable total mean flux decrement. Note that the spectra have not been randomized. Up to 20 per cent of the flux decrement is due to absorption systems with $\log(N_{\rm HI}/{\rm cm}^{-2}) > 15$. In Fig. 3(b) we show a similar plot for the rms fluctuations of the flux. About 15–30 per cent of the flux fluctuations are contributed by absorption from strong lines. Poisson noise of the rare strong absorption systems can thus conceivably explain the significant differences of the mean flux decrement between different lines of sight (Press et al. 1993). Unfortunately the sample is too small to test the evolution of the contribution of strong absorption lines with redshift.

5 STRONG ABSORPTION SYSTEMS AND ESTIMATES OF THE DM POWER SPECTRUM

In the last section we had seen that strong absorption systems contribute significantly to both flux power spectrum and mean flux decrement. This will have important implications for attempts to use numerical simulation together with QSO absorption spectra to infer amplitude and slope of the DM power spectrum with high accuracy. Numerical simulations of the Lyman α forest often underpredict the number of strong absorption systems. The first hydro-simulation investigating high column density systems found that the number of Lyman limit systems fell short by a factor of 10 (Katz et al. 1996) and that a more moderate shortfall extends to smaller column densities (Hernquist et al. 1996). For the strong absorption systems discussed here ($\log(N_{\rm HI}/{\rm cm}^{-2}) > 15$) this problem may have been solved for hydro-simulations with higher resolution (Theuns, Mo & Schaye 2001). The dynamic range of such simulations is, however, still limited and they are expensive in terms of CPU-time. For the analysis of Lyman α flux power spectra numerical simulation of the DM distribution which mimic the effect of gas pressure in an approximate way (so-called 'Hydro-PM' simulations) are widely used. These are simulation for which the discrepancy already becomes large for lines with $\log(N_{\rm HI}/{\rm cm}^{-2}) > 14$ (Gnedin 1998).

The lack of strong absorption systems will affect the inferred matter power spectrum in two ways. If large column densities absorption systems contribute significantly to the observed flux power spectrum on large scales by their shape, their absence has to be compensated by extra power due to density correlations on these scales. This will require a shallower slope of the DM power spectrum. Without detailed numerical simulations it is difficult to estimate how large this bias will be. However, considering the large contribution of strong absorption lines and the weak dependence of the slope of the flux power spectrum on the slope of the DM spectrum it should be a serious concern for upcoming determinations of the DM power spectrum with larger samples of spectra which aim at high accuracy.

The second more subtle bias is due to the effect of strong absorption systems on the mean flux decrement. As discussed e.g. by Croft et al. (1998), the amplitude of the Lyman α flux power spectrum depends not only on the amplitude of the matter power spectrum, but there is also a strong dependence on the mean flux decrement. The amplitude of the flux power spectrum increases with increasing mean flux decrement.

Analyses of observed flux power spectra with numerical simulations therefore normally set the mean flux decrement in the artificial spectra produced from numerical simulations to that of observed spectra. This is a reasonable thing to do if the numerical simulations are a fair representation of the absorbers responsible for the flux decrement in observed spectra. For simulations that do not produce enough strong absorption systems this is not the case. In the case of the hydro-simulations this may be related to the fact that the ionization rate required to match the observed mean flux decrement with favoured values of the baryon density and temperature falls short of that estimated from QSO surveys and high-redshift galaxies by a factor of 2–4 (Rauch et al. 1997; Haehnelt et al. 2001). A population of strong absorption systems may thus be genuinely missing in numerical simulations. In the case of the Hydro-PM simulations, the insufficient spatial resolution is the obvious reason for the much more severe lack of strong absorption systems.

Calibration of numerical simulations which underreproduce observed strong absorption systems using the observed mean flux decrement is thus not the right thing to do. If it is done nevertheless, the amplitude of the matter power spectrum inferred from the Lyman α flux power spectrum will be systematically biased low. The simulated spectra then reproduce the observed flux fluctuations with a larger flux decrement and a smaller matter fluctuation amplitude. This effect is not small. Seljak et al. (2003) found that a 20 per cent reduction of the effective optical depth used to calibrate the simulated spectra leads to a factor of 2 increase of the inferred DM fluctuation amplitude. Note that if the inferred DM fluctuation amplitude at small scales is biased low, a combined analysis with other data on larger scales (CMB, galaxy surveys) will lead to an underestimate of the spectral index. Alternatively, a spurious running of the spectral index may be inferred.

The two effects of a lack of strong absorption systems may, however, cancel to some extent. With a detailed study of spectra from high-resolution hydro-simulations it should be possible to quantify the combined effect.

6 CONCLUSIONS

We used a sample of high-resolution, high signal-to-noise QSO absorption spectra for which line lists of hydrogen and metal absorption systems are available to investigate the effect of discrete absorption systems on Lyman α flux power spectra. The sample was observed with the ESO-UVES spectrograph and the median redshift of the absorbed region is $\langle z \rangle = 2.43$. A random superposition of Voigt profiles contributes significantly to the Lyman α flux power spectrum over a wide range of scales. Only at wavelengths with $k < 0.03$ s km^{-1} a weak clustering signal appears to be detected. However, even there the contribution from strong absorption systems approaches 50 per cent. The contribution of strong absorption systems to the mean flux decrement is also large, up to 20 per cent for strong absorption systems with $\log(N_{\rm HI}/{\rm cm}^{-2}) > 15$. Note, however, that these contribution may be smaller at higher redshift. Simulated absorption spectra often underreproduce the number of strong absorption systems. The use of such simulations calibrated to the observed mean flux for an analysis of Lyman α forest flux power spectrum may lead to an underestimate of the amplitude and initial slope of the inferred DM power spectrum.

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